Cooperative Integration of Harvesting Sections for Passive RFID Communication

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***Abstract*—This paper considers the integration of three attractive concepts: Electromagnetic Energy Harvesting (EEH), Radio Frequency Identification (RFID) communication, and exploiting the non-linear characteristic of RF devices. An EEH circuit is integrated with a passive RFID tag profiting from three non-linear phenomena of rectifying elements: (1) the impedance power dependency, (2) the harmonic production, and (3) the RF waveform dependency. The harmonic signals generated by the rectifier section of a commercial $868\ MHz$ RFID chip, and additionally an external modulated signal at the $2.4\ GHz$ ISM band are harvested by rectifier circuit and are used to supply the RFID chip with additional dc energy in order to increase its sensitivity. A prototype is tested and experimental results show the cooperative effect by maximizing the RF-to-dc conversion efficiency of the EEH section (from $40\ \%$ to $64\ \%$) and simultaneously enhancing the sensitivity of the RFID chip by $7.2\ dB$.**

***Index Terms*—RFID, UHF passive tags, sensor, non-linearity, harmonics, rectifier, harmonic balance, wireless power transfer.**

I. Introduction

The requirement of additional functions for smart tags in the Internet of Things (IoT) deployment has raised the need of additional sources of energy [1]. Among the possible energy sources, the natural or ecologic sources such as solar, motion, human body are of first interest. Besides, another relevant approach is the use of wasted ambient electromagnetic energy. It can constitute a suitable powering source. Additionally, the technology that best suits the requirements in terms of low power wireless communication is the passive RFID technology due its Wireless Power Transmission (WPT) operation [2].

The design of Electromagnetic Energy Harvesting (EEH) devices among them passive RFID tags and rectennas, requires the developing of efficient transmission and reception power transfer techniques. These techniques have been addressed in the literature in a direct or indirect manner by considering the non-linear behavior of EEH devices. Actually, it is possible to classify the non-linear phenomena reported for EEH and WPT applications in three main categories: (1) impedance-power dependency [3], [4], (2) harmonic generation [5]–[7], and (3) efficient waveform design [8], [9].

The main aim of this paper is to integrate an EEH device and a passive RFID tag seeking for a mutual benefit that purposely considers for each part, the three non-linear phenomena enumerated in the previous paragraph. A prototype was built and tests show a sensitivity enhancement of $7.2\ dB$ when EEH and RFID sections operate together.

II. Multi-device Harvesting Enhancement

For the proposed approach, the integration architecture, hereinafter so-called Tag-Harvester (TH) is depicted in Fig. 1. The global performance enhancement is based in the simultaneous operation of the RFID and EEH sections as follows: (1) the non-linear signals generated by the RFID section are reflected into the EEH section in order to generate a profitable waveform for rectification. (2) the harvested direct current (dc) of the EEH section is re-injected into the RFID section aiming to enhance the chip sensitivity. The re-injection of the dc can be done using a Battery Assisted Power (BAP) RFID chip which has an auxiliary dc supply pin.

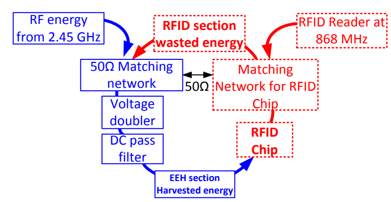

Fig. 1. Architecture of the proposed TH. A mutual benefit is seek when EEH section and RFID section operates simultaneously

The beneficial effect of the RFID section to the input signal of the EEH section can be explained by the waveform design technique used for efficient WPT. The literature explains the technique by using *time varying envelope signals* [8], [9]. Signal waveforms are capable to activate rectifying devices for lower average input power levels, compared to signals of constant envelope and the same average power. Therefore, when higher the Peak-to-Average Power Ratio (PAPR) is in the received signal, higher is the rectifier RF-to-dc conversion efficiency. In this context, the EEH section of the TH seeks for receiving a higher PAPR signal. The proposed approach aims to meet this requirement by using the modulated harmonics produced by the RFID chip and reflected towards the EEH section producing a waveform signal with higher PAPR.

III. Emulated Prototype

A. EHH Section

EEH from RF signals at $2.45\ GHz$ is achieved using a voltage doubler circuit consisting of two stages using Skyworks SMS7630 Schottkty diodes similar to [4]. The schematic circuit is shown in Fig. 2(a). The first stage is formed by a series capacitor ($C1 = 1.2\ pF$) and a shunt diode (D1). The second stage uses a series diode (D2) and a shunt capacitor ($C2 = 2.7\ pF$). The rectifier input is matched to 50 Ω using an L-network consisting of a shunt $L1 = 1\ nH$ and a series inductor $L2 = 3.9\ nH$. The rectifier dc output is connected to a resistance R_L. Given the non-linear dependency of the rectifier impedance with the input power, the matching is optimized by simulation to maximize the RF-to-dc conversion efficiency for low input power using Agilent's harmonic balance. The RF-to-dc efficiency defined as in [4], is maximum when $R_L = 5\ k\Omega$. The dc output of the EHH section is provided to the RFID chip.

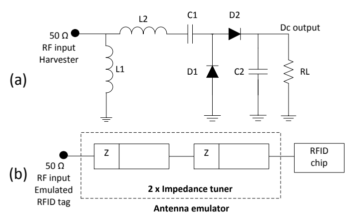

Fig. 2. Schematic representation of the prototype. (a) Harvester circuit, (b) emulated passive RFID tag.

B. RFID Section

The 50 Ω RFID section is composed by two parts: (1) the antenna emulator composed by two impedance tuners Microlab SF-30F connected in series, and (2) the BAP RFID chip EM4325 fixed in a SMA connector [5]. The RFID chip is powered by the RFID reader at 868 MHz and additionally by the available dc energy received in its auxiliary dc pin. The schematic RFID tag is shown in Fig. 2(b). The operation of the emulated RFID tag is as follows: (1) the antenna emulator provides the complex conjugate impedance of the chip impedance, which represents the impedance of an optimum RFID tag antenna. (2) When the matching is achieved, the chip is in scavenging state and, once activated, it switches between the two modulation states.

IV. Experimental Evaluation

A. Measurement Setup

Conducted measurements were performed to evaluate the performance of the TH. The experimental tests have two goals: (1) to measure the dc output across the load resistor in the EEH section, and (2) to measure the RFID chip sensitivity when the harvested power is re-injected. The schematic setup illustrated in Fig. 3 comprises three directional couplers that allows to connect the EEH section and the RFID section with an external source at 2.45 GHz (Agilent N5182A Vector Signal Generator (VSG)), a Speedway Revolution RFID reader, and an oscilloscope to visualize the interaction of sections in time and frequency domains (Agilent 91204 Digital storage oscilloscope). A computer allows to control the RFID reader in order to activate the emulated RFID tag. A multimeter is used to measure the dc output of the EEH. The setup is calibrated in order to measure the effective power injected in the harvester circuit and in the RFID chip.

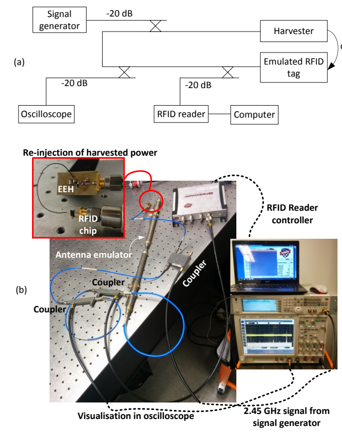

Fig. 3. Measurement setup to evaluate the performance of the TH. (a) Schematic of the interconnection. (b) Equipment setup.

Two transmission configurations are considered to better evaluate the operation of the TH: (1) only EEH section operating and (2) EEH section and RFID section operating simultaneously. To emulate a modulated signal at 2.45 GHz as those ones from ambient signals, the RF source generates in all cases an Amplitude Shift Key signal. The RFID reader transmits always the minimum power that activates the RFID tag.

B. EEH Evaluation

Fig. 4 shows the measured dc output voltage of the EEH section in function of its input power for both transmission configurations. It can be observed that when both RF sources are active, the harvested dc level has an exponential growth with the input power.

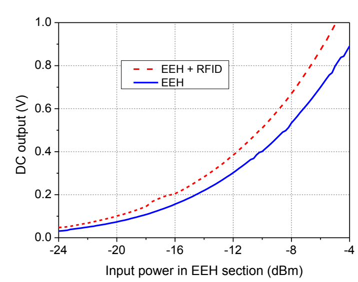

Fig. 4. Harvested dc output in function of the input power at 2.45 GHz.

In order to quantify the improvement, Fig. 5 shows the RF-to-dc conversion efficiency for both transmission configurations. A considerable enhancement can be noted when both RF sources are active. At low input power ($-24\ dBm$) the efficiency increases from 5 % to 10 % while at higher input power ($-4\ dBm$) the efficiency increases from 40 % to 64 %. Fig. 6 shows the normalized power spectral density for both transmission configurations compared to the noise level. When both RF sources are active the spectrum is composed by the fundamental signals of each section and the 2^{nd} and 3^{rd} harmonic of the RFID section. Even if the EEH section is optimized for 2.45 GHz, the modulated harmonics alters the waveform received by the EEH section and cause the enhanced RF-to-dc conversion efficiency.

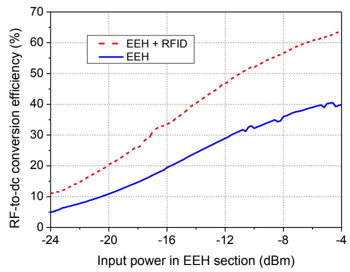

Fig. 5. RF-to-dc conversion efficiency of the harvested circuit in function of the input power at 2.45 GHz. When EEH section and RFID section operate simultaneously, the conversion efficiency is higher.

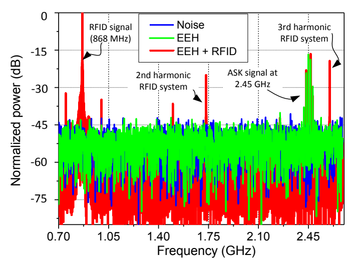

Fig. 6. Normalized power spectral density visualized in the oscilloscope when the sections are interconnected. When both sources are active, the richest spectrum favors the conversion efficiency of the harvester circuit.

The great difference from the measured dc with only the EEH section active compared to the case of both section operating simultaneously demonstrates the mutual enhanced performance.

C. Tag Sensitivity Evaluation

The performance of the TH as RFID tag is evaluated by measuring the chip sensitivity when the harvested dc power is re-injected. The power transmitted by the RFID reader is controlled in order to acquire the chip activation threshold for each input power in the EEH section. The RFID chip sensitivity variation with respect to input power in the EEH section is shown in Fig. 7. It can be observed that above $-8\ dBm$, the BAP mode of the RFID chip starts operating and the sensitivity of the chip increases. The measured sensitivity enhancement of 7.2 dB allows to multiply the read range of an RFID tag by a factor of 2.3.

V. Conclusion

The work presented in this paper proposes to exploit the non-linearity of diode-based rectifier devices by re-purposing

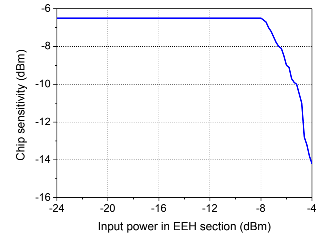

Fig. 7. Sensitivity of the RFID chip in function of the input power at 2.45 GHz in the harvester section. Above $-8\ dBm$, the BAP mode of the RFID chip starts operating and the sensitivity of the chip increases.

the theory used for WPT to benefit the joint operation of an EEH device with a passive RFID tag. The prototype consists of an emulated RFID tag operating at 868 MHz and an EEH circuit operating at 2.45 GHz, both integrated to operate with a mutual enhanced performance. Experimental results demonstrate an enhancement in the RF-to-dc conversion efficiency from 40 % (only EEH operating) to 64 % (EEH and RFID operating simultaneously) which turns in a 7.2 dB enhancement of the RFID chip sensitivity.

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